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Magnetic Field Parameters of HGQ06 Coil Ends

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1 Introduction

A preliminary magnetic field optimization of HGQ ends was presented in Ref. [1]. The study was based only on magnetic field parameters. It was shown that within the original 4-block design, a significant improvement of the field quality, especially in the lead end, and some improvement of the other magnetic parameters (peak field and magnetic length) could be obtained by re-optimizing the origin differences of the conductor groups. In order to provide better mechanical performance, it was later decided to split the 11 conductor group of the inner layer in two smaller groups. The new conductor groups have been mechanically optimized using BEND. A magnetic field optimization of this 5-block configuration was then carried out by adjusting the relative longitudinal positions of the conductor groups, and the resulting magnetic parameters are presented here. It is presently planned to implement this end design in magnet HGQ06.

2 Computer model

The magnetic field analysis has been performed using program ROXIE. Details on this program, and on the method for building the computer model of the coil from the BEND coordinate files can be found in Ref. [2]. The iron yoke is modeled as a magnetic mirror of circular shape (radius 9.256 cm) with infinite permeability. Each conductor has been subdivided in current filaments, one for each strand. The total number of strands is 38 in the inner layer, 46 in the outer layer. The lead and return end fields are analyzed separately. For both the lead and the return end calculations, a straight section extending in the negative z direction for 1.5 m from the start of the iron yoke towards the magnet body is included in the model. The geometry of the conductor groups has been optimized for best mechanical performance using program BEND. The following figures and tables show the BEND definitions for the conductor groups, the corresponding ROXIE block/conductor definitions, and the resulting 3D models for the lead and return end. Table 3 shows the origin differences for the conductor groups. Table 4 shows the maximum longitudinal position of the cable in the outermost conductor groups, in the lead and return end (the origin differences are not included).

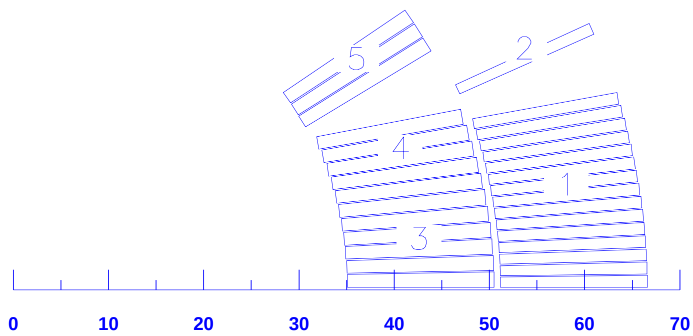

Figure 1: Coil cross-section model for the HGQ return end. Axis scale is in mm.

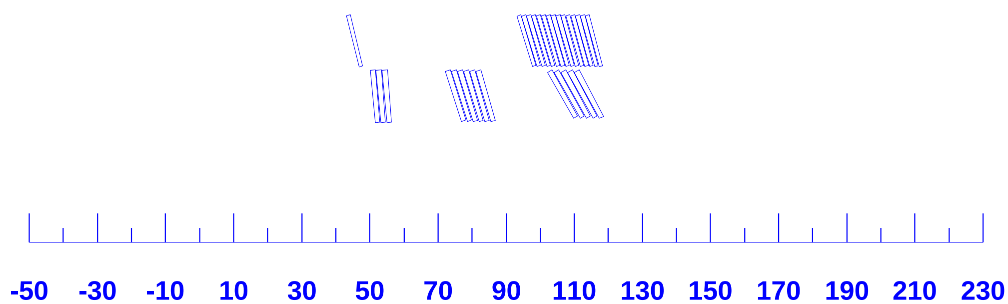

Figure 2: Longitudinal positions of the conductor groups at the pole angle, for the return end

ROXIE		BEND	No. turns	Description
Block #	Turn #	Group		
1	1 to 15	q2or312	15	2^{nd} wound, outer
2	16	q1or01	1	1^{st} wound, outer
3	17 to 21	r3ir05	5	3^{rd} wound, inner
4	22 to 27	r2ir06	6	2^{nd} wound, inner
5	28 to 30	q1ir03	3	1^{st} wound, inner

Table 1: Block and turn definitions for the return end.

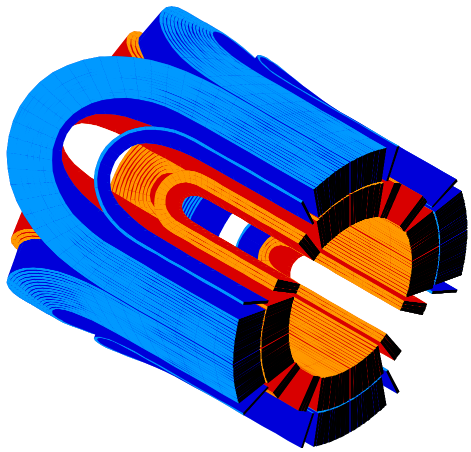

Figure 3: ROXIE-BEND model for the return end (only the part of the coil extending beyond the edge of the iron yoke is shown).

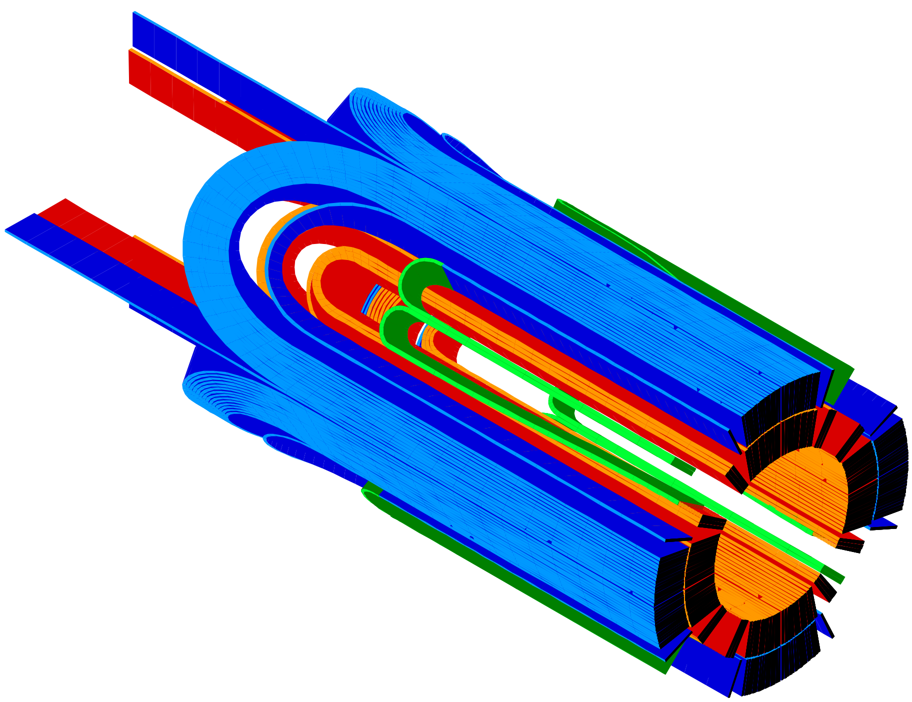

Figure 4: ROXIE-BEND model for the lead end (only the part of the coil extending beyond the edge of the iron yoke is shown).

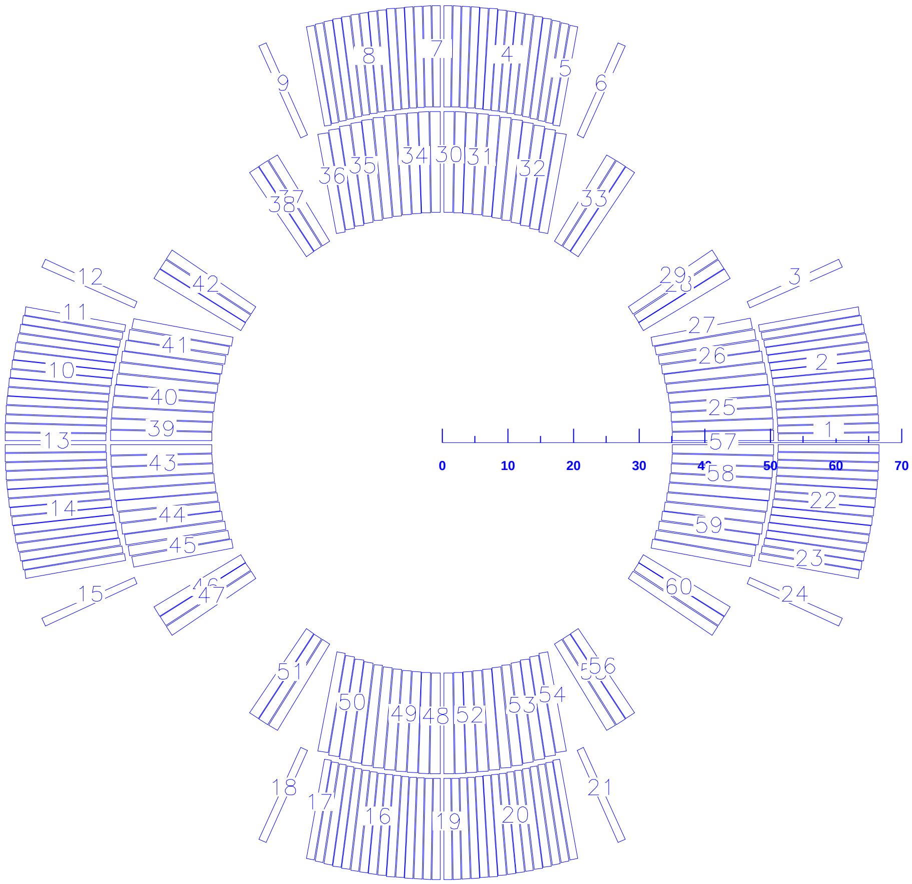

Figure 5: Coil cross-section model for the HGQ lead end. The axis scale is in mm.

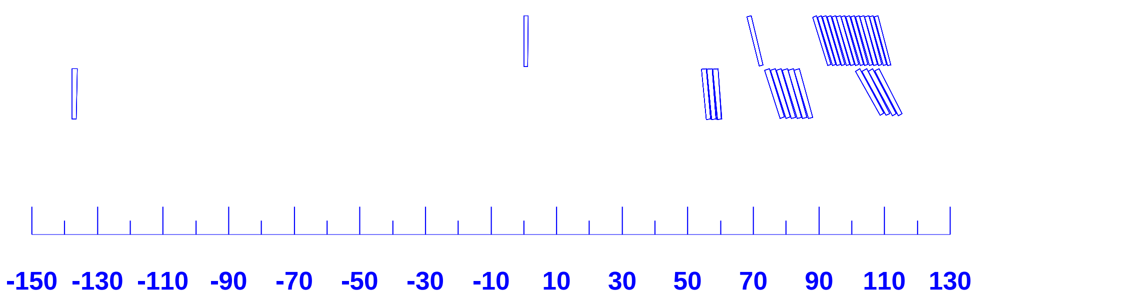

Figure 6: Longitudinal positions of the conductor groups at the pole angle, for the lead end. The vertical bars indicate the end of the straight section for the splice conductors.

ROXIE				BEND	No. turns	Description
Blk	Turn	Conn. blk	End type	Group		
1	1		1		1	Straight to quadrant splice
2	2 to 15	4	2	q2ol311	14	2^{nd} wound, outer, left
3	16	5	3	q1or01	1	1^{st} wound, outer, left
4	17 to 30	2	7	q2ol212	1	2^{st} wound, outer, right
5	31	3	8	q1ol01	1	2^{st} wound, outer, right
6	32	29	12	qoa/b	1	Ramp to coil spilce (outer)
25	129 to 132	31	14	reil04b	4	3^{rd} wound, inner, left
26	133 to 138	32	15	r2il06	6	2^{nd} wound, inner, left
27	139	33	5	q1il01	1	2^{nd} to 1^{st} wound
28	140 to 141	33	6	q1il02	2	1^{st} wound, inner, left
29	142	6	13	qia/b	1	Ramp to coil splice (inner)
30	143		9		1	Straight to quadrant splice
31	144 to 147	25	16	r3il04a	4	3^{rd} wound, inner, right
32	148 to 153	26	17	r2ir06	6	2^{nd} wound, inner, right
33	154 to 156	27,28	11	q1ir03	3	1^{st} wound, inner, right

Table 2: Block and turn definitions for the lead end (first quadrant).

Group	Return end	Lead end
2^{nd} wound, outer	25	20
1^{st} wound, outer	0	25
3^{rd} wound, inner	62	61
2^{nd} wound, inner	34	35.3
1^{st} wound, inner	32	36

Table 3: Origin differences [mm] for the conductor groups in the lead and return end

End/coil	HGQS06		HGQS03	
	Group	Al_{max}/OD	Group	Al_{max}/OD
Return end, inner coil	r3ir05	57.3/62	q2ir29	60.6/46
Return end, outer coil	q2or312	96.5/25	q2or312	96.5/20
Lead end, inner coil	r3il04b	55.4/61	q2il19	58.8/46
Lead end, outer coil	q2ol212	95.0/20	q2ol212	95.0/20

Table 4: Maximum longitudinal position of the groups (mm). Max A-length/Origin Difference.

3 Magnetic field parameters

For definitions of the various quantities, see for example Ref. [3]. For general HGQ conventions for reference frame and field quality representation, see Ref. [4].

Conductor group	Return end		Lead end	
	HGQ06	HGQ03	HGQ06	HGQ03
Inner, 1^{st} wound	0.66	0.66	0.65	0.64
Inner, 2^{nd} wound	0.60	0.63	0.60	0.61
Inner, 3^{rd} wound	0.58		0.58	
Inner, ramp to splice			0.64	0.64
Outer, 1^{st} wound	0.53	0.54	0.55	0.54
Outer, 2^{nd} wound	0.56	0.57	0.55	0.57
Outer, ramp to splice			0.53	0.53

Table 5: Field load line coefficients B^{max}/I (T/kA) in the lead and return end regions.

Block #	Turn #	B^{max}/I (T/kA)	
		I=1kA	I=14kA
1	15	0.60	0.58
2	16	0.59	0.57
3	27	0.65	0.63
4	30	0.71	0.69

Table 6: Field load line coefficients in the magnet body, at low and high current [5].

Table 5 reports the field load line coefficients for each block in the lead and return end. The corresponding parameters for magnet HGQ03 (same as for magnet HGQ04 and HGQ05) are also given for comparison [3]. Looking at the return end, the peak field in the first wound conductor group of the inner layer is comparable for the two designs. It should be noted that since the new design is more compact, the peak field in the first-wound conductor group tends to increase by about 2%. In order to keep it on the same level as before, the first conductor group of the outer coil was shifted back to zero origin difference. This however prevents the possibility of cutting some thickness out of the keys in both inner and outer coil (all other groups have nonzero origin difference). The peak field in the conductor block that has been split in two is decreased by 5% in the new design. For the outer coil, there is a reduction of the peak field of about 2% for both groups.

For the lead end, in both designs the peak field is generally lower than in the return end. For this reason, it was decided for the lead end to maintain a nonzero origin difference for the first-wound group of the outer coil. As a result, the peak field in the lead end is increased by 2% with respect to the previous design (but still lower than in the return end). In the outer coil, the peak field is decreased by about 2% with respect to the previous design.

Tables 7 and 8 report the magnetic length and field quality parameters for the lead and return ends. The corresponding parameters for magnet HGQ03 (same as for magnet HGQ04 and HGQ05) are also given for comparison [3]. With the new design, the magnetic length is slighlty increased in both the lead and the return end. The field quality is also improved, in particular for the return end. In the lead end, the normal dodecapole is decreased by about 30% with this 5-block design, while with the 4-block design optimization a reduction by 80% could be obtained [1].

Parameter	HGQS06	HGQS03
L_m (cm)	42.0	41.4
$\hat{b}_2$	10000	10000
$\hat{b}_6$	3.5	5.0
$\hat{b}_{10}$	-0.1	-0.2
$\hat{b}_{14}$	0.0	0.0
$\hat{a}_2$	46.1	43.8
$\hat{a}_6$	-0.7	-0.3
$\hat{a}_{10}$	0.0	0.0
$\hat{a}_{14}$	0.0	0.0

Table 7: Integrated harmonic coefficients for the lead end. The integration interval starts at z=-35 cm and ends at z=+25 cm. The physical length from z=-35 cm to the end of the coil is 46.64 cm for HGQ06 and 46.50 cm for HGQ03.

Parameter	HGQS06	HGQS03
L_m (cm)	32.9	32.5
$\hat{b}_2$	10000	10000
$\hat{b}_6$	0.1	1.2
$\hat{b}_{10}$	-0.1	-0.3
$\hat{b}_{14}$	0.0	0.0

Table 8: Integrated harmonic coefficients for the return end. The integration interval starts at $z = -25$ cm and ends at z=+25 cm. The physical length from z=-35 cm to the end of the coil is 37.15 cm for both HGQ06 and HGQ03.

4 Conclusions

Results of magnetic field calculations for the new 5-block design of the HGQ coil ends have been presented. The peak field is in the inner coil is unchanged. The peak field is in the outer coil is reduced by about 2%. The magnetic length vs. physical length ratio is improved by 4 mm in both lead and return end. The calculated normal dodecapole is decreased by 30% in the lead end, and it is close to zero in the return end.

References

[1] G. Sabbi, "Preliminary magnetic field optimization of HGQ05 End Regions", Fermilab TD-98-037, May 1998.

[2] ROXIE, Routine for the Optimization of Magnet X-Sections, Inverse Field Computation and Coil End Design. Proceedings of the First International Roxie Workshop, Geneva, March 1998.

[3] G. Sabbi, "HGQ03 End Field Analysis", Fermilab TD-98-010, February 1998.

[4] J. DiMarco, et al., "Conventions for HGQ Field Quality Representation", Fermilab TD-98-034, May 1998.

[5] G. Sabbi, "Load lines and short sample limits for HGQ model S01", Fermilab TD-97-011, April 1997.